

Mercury and Lead Contamination in Three Fish Species and Sediments from Lake Rukwa and Catchment Areas in Tanzania

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Introduction

Lake Rukwa is one of the principal freshwater resources of Tanzania, meeting demands for drinking water, transport and fishery activities. Contamination of fresh water with heavy metals and pesticides is a matter of great concern in this region, as it is globally. Pollution of Lake Rukwa and rivers in the catchment area may have devastating effects to public water supplies and aquatic life, and lead to effects to human health. Pollution by heavy metals such as mercury (Hg), lead (Pb) and chromium (Cr), in particular, tend to reduce the quality of ecosystems on which all humans depend for daily life. The lake and its catchment area is known as a biodiversity hotspot as it supports numerous fish species, crocodiles, water birds and hippopotamuses. The ecosystem also provides services like food, recreation, medicine, transport and domestic water to the surrounding communities and beyond. Fish species of commercial importance include Rukwa tilapia (*Oreochromis rukwaensis*), introduced Singida

Background. Mining activity in the catchment area of Tanzania's Lake Rukwa is suspected of adding to the lake and connected rivers' heavy metal load. There has been no study done, however, on the levels of mercury (Hg) and lead (Pb) in lake sediment and fish muscle, and what the results could mean for human health.

Objectives. This study investigated the concentration of Hg and Pb in lake sediment and in the muscles of African sharptooth catfish (*Clarias gariepinus*), Lake Rukwa tilapia (*Oreochromis rukwaensis*) and Singida tilapia (*Oreochromis esculentus*) from Tanzania's Lake Rukwa and connected rivers.

Methods. Concentrations of Hg and Pb in fish muscle and lake sediment were measured using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and mercury analyzers, respectively.

Results. Levels of Pb and Hg from *C. gariepinus* ranged between 0.01 to 1.9 µg/g and 0.03 to 0.33 µg/g, respectively. Pb and Hg in *O. esculentus* varied between 0.02 to 1.4 µg/g and <0.01 to 0.29 µg/g, respectively. Pb and Hg levels in *O. rukwaensis* ranged from 0.12 to 0.88 µg/g and 0.12 to 0.88 µg/g, respectively. On the other hand, concentrations of Pb and Hg in the sediment samples ranged between 0.02 to 16.23 µg/g and from 0.01 to 1.43 µg/g, respectively. Concentrations of Hg in the muscles of *C. gariepinus* and *O. esculentus* were above World Health Organization (WHO) permissible limits, indicating that they are not safe for human consumption. Concentrations of Pb in fish muscle samples were below WHO permissible limits and United States Environmental Protection Agency (USEPA) provisional tolerable weekly intake (PTWI) standards. Furthermore, Hg and Pb in sediment were below the threshold value of Environment Canada and Florida's 'No effect level'.

Conclusions. Although levels of Pb in fish samples and Hg and Pb levels in sediment were below international standards, it is important to consider that fish forms an important source of animal protein for local inhabitants, who are likely to consume more fish than considered by these standards. The study recommends further research on the levels of mercury and lead in humans, especially children and pregnant women.

Competing Interests. The authors declare no competing financial interests.

Keywords. Lake Rukwa Tanzania, *Clarias gariepinus*, *Oreochromis esculentus*, *Oreochromis rukwaensis*, muscles, sediments, mercury, lead, WHO, FAO, EPA's PTWI

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tilapia (*Oreochromis esculentus*), Redbreast tilapia (*Coptodon rendalli*, or *Tilapia rendalli*) and African sharptooth catfish (*Clarias gariepinus*), among others.¹ These species are important sources of animal protein, employment and income generation for the local residents.

Like many other water bodies, Lake Rukwa has the unfortunate handicap of being situated downstream of humans, thus receiving significant anthropogenic inputs. Recently, small- and medium-scale gold mining have been developed in the catchment areas of Lake Rukwa. The techniques used vary from simple hand-powered operations like gravity

panning to more diverse methods, including amalgamation and cyanide leaching. The latter methods are thought to be increasing the levels of Hg in the rivers and lake because they involve the use of the metal to extract visible gold and the extraction process in our study area takes place in the vicinity of the Luika and Songwe rivers. Unfortunately, mining areas around Lake Rukwa lack waste treatment systems; untreated waste is discharged directly into the waterways or enters the lake through runoff during the rainy season via a network of streams and rivers. In addition, mining has attracted a large number of people to the area, consequently increasing anthropogenic wastes that contain harmful metals, such as Pb.

Following mining activities in the area, there has been public concern that fish and water from Lake Rukwa may no longer be safe for human or livestock consumption. Most of the surrounding communities get their domestic water supply and animal protein from the lake, rivers and streams. It is for this reason that key information on the concentration of Hg and Pb within the aquatic environment and the potential danger of fish contamination to the public health need to be assessed and quantified.

Hg occurs naturally as a mineral and is widely distributed throughout the environment as a result of both natural and human activities. Inorganic mercury is the most common form of the metal released into the environment by industrial activity. Once in the aquatic environment, part of inorganic mercury is microbiologically converted to methylmercury, which is rapidly absorbed through gills, skin and the digestive tract of fish. Worldwide, gold mining is commonly

Abbreviations			
BIS	Bureau of Indian Standards	km	Kilometer
C	Celsius	m	Meter
CBR	Community Bureau of Reference	mm	Millimeter
Cd	Cadmium	MRF	Malaysia—Food and Agricultural Import Regulations and Standards
Cr	Chromium	Pb	Lead
EOS	Egyptian Organization for Standardization and Quality Control	PTWI	Provisional tolerable weekly intake
FRS	Food Safety Law and Regulation Singapore	WHO	World Health Organization
FSA	Food Standards Australia New Zealand	µg/g	Micrograms per gram
		µg/kg	Microgram per kilogramer
g	Gram	µm	Micrometer
Hg	Mercury	USEPA	United States Environmental Protection Agency
ICP-AES	Inductively coupled plasma atomic emission spectroscopy		

held to be responsible for much of the mercury contamination of aquatic ecosystems.² It has been reported that artisanal gold mining releases up to 1350 tons of Hg to the global environment annually.³ Furthermore, research has documented that other heavy metals are also highly toxic and persistent in the environment causing serious health hazards in ecosystems and to people.⁴⁻⁸ Hg, Pb and cadmium (Cd) are especially of concern because they are known to cause diseases globally. These include: Minamata disease (organic mercury poisoning), Itai-itai disease (cadmium poisoning), arsenous acid (H₃AsO₃) poisoning, and air pollution-related asthma.⁹ Further studies by Olaifa et al. have shown that fish are particularly

affected by these pollutants, thus are widely used to assess the health of aquatic ecosystems.¹⁰ It is clear that high concentrations of Hg in fish can lead to pathological alterations, with subsequent inhibition of metabolic processes, hematological changes and decline in fertility and survival.¹¹ In Nigeria, an elevated concentration of Hg and Pb in the Aba River was investigated as contamination of shellfish and other aquatic food was a matter of concern to the public health.⁸ Also, Jonathan and Maina investigated the accumulation of heavy metal in mudfish (*Clarias anguillaris*) and African bonytongue (*Heterotis niloticus*) in Lake Geriyo, Nigeria.¹² Guimarães and Lacerda reported that most of the aquatic organisms, including fish and plants, accumulate metals up to 10⁵ of the



Figure 1 — Map of Lake Rukwa Showing Sampling Sites
A) Rungwa river; B) Momba river; C) Songwe river; D) Luika river; E) Maleza; F) Kambi Potea

levels present in the environment.¹³ A number of studies reported that the occurrence of heavy metals in rivers, lakes or any other aquatic environment could change both aquatic species diversity and ecosystem health due to toxicity and accumulative behavior.¹⁴ Consequently, humans can be contaminated by heavy metals that are associated with an aquatic system by consumption of contaminated fish and other aquatic food.¹⁵ Environmental and health impacts resulting from heavy metal require both coordinated action and global responses. However, these responses can only come after enough data has been collected on the level of heavy metal resulting from anthropogenic activities. Because of the importance of Lake Rukwa to the fishery, tourism and domestic water supply of Tanzania, it is important to investigate and quantify Hg and Pb levels in the aquatic environment and its implication to human health.

Methods

Description of the Study Site

This study was conducted in the southern and northern part of Lake Rukwa, Tanzania (Figure 1). The southern part of the lake includes study areas Songwe River, Luika River, Maleza, and Kambi Potea. The northern and western parts refer to Rungwa and Momba rivers, respectively. The lake is located in southwestern Tanzania, in eastern Africa. It has a length of about 165 km, width of 37 km on the north basin and a maximum width of 48 km near the middle of the lake.¹⁶ The lake covers an area of about 1,000 square miles (2,600 square km) and lies midway between Lake Tanganyika and Lake Nyasa. It has an average depth of 10 feet (3 m). Its drainage basin has an area of 31,000 square miles (80,000 square km) in Tanzania. There is no outlet from the lake and fluctuations in size are caused by the varying inflow of streams and rivers.

There are several large tributaries to the lake. The Lupa, Luika, and Songwe rivers drain the Mbeya Range and flow into the lake from the south, the Rungwa feeds the lake from the north, and the Momba River flows in from the west. There is one rainy season, falling from October to April, and dry conditions are experienced from May to October. Average annual rainfall ranges from about 650 mm in the south of the basin, about 900 mm in the north, to about 2,500 mm in the Ufipa Highlands.¹⁶ In the southern portion of the area, the mean annual temperature is 210°C.¹⁷ The surface water temperature ranges between 200°C to 350°C.¹⁶

Sampling Design

In the lake, 2 sites, namely Maleza and Kambi Potea, were selected. For the Luika, Songwe, Momba and Rungwa rivers, 3 sites each were selected for sample collection. The 1st sampling site was set at the river mouth and the 2nd sampling site was selected

1.5 km upstream of the river mouth. The 3rd sampling site was located further upstream, near mining areas. The selection of the 3rd sampling site at Luika and Songwe rivers were based on the presence of mining in the catchment areas. For the Momba and Rungwa rivers, samples were collected 4.5 km from the 2nd sampling site. In the lake, Kambi Potea and Maleza were selected based on the potential of the areas for fishing and their proximity to the mouths of the Luika and Songwe rivers (Figure 1). In the Rungwa and Momba rivers, samples were collected at -7.436314S 31.773839E, -7.424058S 31.757360E, -7.413163S 31.740880E and -8.250150S 32.439714E, -8.254227S 32.425294E, -8.261362S 32.418771E, respectively. In the Songwe and Luika rivers, samples were collected from points -8.453789S 32.925859E, -8.459901S 32.932725E, -8.605896S 33.039842E and -8.487067S 32.916932E, -8.498612S 32.912812E, -8.604538S 32.917619E, respectively. In Maleza and Kambi Potea, samples were collected from -8.428658S 32.824235E and -8.404205S 32.701326E.

Sample Collection and Digestion

Sediment and fish samples were collected in April and August 2014. Samples of *C. gariepinus*, *O. rukwaensis*, and *O. esculentus* and sediment were collected from selected sites for Hg and Pb analysis. A total of 8 *O. rukwaensis*, 24 *O. esculentus* and 40 *C. gariepinus* muscle samples were collected using beach seine and gill nets. The fishes were dissected and care was taken to avoid external contamination of the samples. A sterilized rust-free stainless steel kit was used to dissect the fish. Non-edible parts (fins, scales, intestine) were removed and muscle tissue was stored before air-drying and then dried in an oven at 60°C until constant weight was obtained. The

dried samples were crushed into fine powder. The resulting fine powder was stored in a dark unit for digestion. Fifty-six samples of sediment were collected using a sediment corer and placed in pre-labeled transparent polythene bottles rinsed with 10.0% HNO₃ and kept in an ice chest at <4°C. Sediments were wet-sieved through a 100 µm mesh plastic screen, and the fraction of <100 µm were used for analysis. Samples were frozen at -200°C before elemental analysis. Samples were transported to SEAMIC Chemistry Laboratory in Tanzania for analysis.

In the laboratory, frozen samples of fish muscles were thawed at room temperature and separately oven-dried to constant weight and grounded to powder using mortar and pestle. About 20 g sub samples of muscles tissues were taken and digested in a Teflon cup with concentrated HNO₃ at 105 ± 20°C for 8 hours and frozen before analysis. The powdered samples were digested, and the digests kept in sterile plastic bottles prior to analysis.¹⁸ The concentration of Pb and Hg were determined using ICP-AES and a mercury analyzer, respectively. International standards from the Community Bureau of Reference (CBR) were used to check for the precision and accuracy of analysis.

Data Analysis

Statistical analysis was conducted in a computer program known as GraphPad InStat and STATICA 7. Two-sample t-tests were used to assess variations in the concentration of Hg and Pb in sediment and fish muscle between the sampling sites ($P < 0.05$). Pearson's correlation was used to assess the relationship between the concentration of Hg and Pb in fish muscle and sediment. Tables were used for data presentation. In addition, to ascertain the safety and

the degree of health risks associated with consuming contaminated fish caught from Lake Rukwa and its catchment areas, results were compared with the permissible limits as set by the World Health Organization (WHO), the United States Environmental Protection Agency (USEPA) provisional tolerable weekly intake (PTWI), and the Food and Agriculture Organization and the World Health Organization (FAO/WHO Codex), among other national and international standards.¹⁹⁻²² Furthermore, sediment samples were compared with the allowable criteria of Environment Canada and the state of Florida's 'No effect level' according to MacDonald.^{23, 24}

Results

The results of Pb and Hg concentrations (µg/g) measured in muscles of *C. gariepinus*, *O. esculentus* and *O. rukwaensis* are shown in Table 1.

Lead (Pb) contamination in *C. gariepinus*

The value of Pb in *C. gariepinus* ranged between 0.01 to 1.9 µg/g in both dry and rain seasons. The highest (1.88±0.009 µg/g) recorded mean value of Pb was recorded from the Luika River mouth during the dry season. The lowest (0.01±0.001 µg/g) mean values of Pb in the muscles of *C. gariepinus* were recorded from the mouth of the Rungwa River in the dry season. The lowest (0.5±0.02 µg/g) mean value of Pb from the sites in the lake were recorded from Maleza during the rainy season (Table 1). The highest recorded value (1.44±0.01 µg/g) of Pb from the lake sites was measured from Kambi Potea. The value of Pb from all areas in the Songwe and Luika rivers were not different from the corresponding value measured from Kambi Potea and the Maleza ($P > 0.05$). This is an indication of an even distribution in

Study Sites	Fish Species											
	<i>O. esculentus</i>				<i>O. rukwaensis</i>				<i>C. gariepinus</i>			
	Rainy Season		Dry Season		Rainy Season		Dry Season		Rainy Season		Dry Season	
	PB	HG	PB	HG	PB	HG	PB	HG	PB	HG	PB	HG
*Maleza	0.17± 0.003	0.16± 0.01	0.29± 0.02	0.15± 0.05	0.77± 0.03	0.11± 0.07	0.55± 0.018	0.11± 0.004	0.74± 0.13	0.18± 0.07	0.5± 0.02	0.25± 0.002
*Kambi Potea	0.62± 0.01	0.13± 0.05	0.73± 0.01	0.11± 0.003	0.53± 0.31	0.10± 0.001	0.4± 0.05	0.09± 0.001	0.65± 0.01	0.14± 0.01	1.44± 0.01	0.22± 0.015
Luika River Mouth	0.71± 0.02	0.23± 0.001	0.3± 0.95	0.21± 0.003	×	×	×	×	0.63± 0.85	0.19± 0.002	1.88± 0.009	0.27± 0.016
Luika River Middle	0.63± 0.85	0.21± 0.22	0.37± 0.02	0.17± 0.002	×	×	×	×	0.29± 0.002	0.17± 0.01	0.54± 0.008	0.23± 0.02
Luika River Upper	×	×	×	×	×	×	×	×	×	×	×	×
Sogwe River Mouth	0.83± 0.001	0.17± 0.04	0.98± 0.04	0.21± 0.19	×	×	×	×	0.96± 0.10	0.23± 0.25	0.7± 0.004	0.19± 0.006
Songwe River Middle	0.51± 0.04	0.12± 0.51	0.23± 0.03	0.11± 0.03	×	×	×	×	0.53± 0.01	0.14± 0.05	0.87± 0.03	0.13± 0.03
Songwe River Upper	×	×	×	×	×	×	×	×	×	×	×	×
Rungwa River Mouth	×	×	×	×	×	×	×	×	0.04± 0.04	0.08± 0.001	0.007± 0.001	0.01± 0.001
Rungwa River Middle	×	×	×	×	×	×	×	×	0.021± 0.02	0.02± 0.01	0.019± 0.02	0.017± 0.14
Rungwa River Upper	×	×	×	×	×	×	×	×	×	×	×	×
Momba River Mouth	×	×	×	×	×	×	×	×	0.02± 0.01	0.01± 0.0	0.032± 0.23	0.078± 0.01
Momba Rive Middle	×	×	×	×	×	×	×	×	0.01± 0.006	0.02± 0.01	0.01± 0.24	0.03± 0.008
Momba River Upper	×	×	×	×	×	×	×	×	×	×	×	×

Table 1 — Concentration of Mercury (Hg) and Lead (Pb) in Fish Samples Collected From Lake Rukwa and Catchment Areas
 * indicates sites on the lake, × indicates absence of fish samples

the levels of metal between the study areas. Further analysis revealed that values of Pb from areas including Maleza, Kambi Potea, Luika and Songwe rivers were significantly higher than values from the Rungwa and Momba Rivers ($P < 0.05$), suggesting that *C. gariepinus* from the southern

part of the lake are largely contaminated with Pb compared to the samples from the northern part. The study did not reveal differences in the value of Pb in the muscles of *C. gariepinus* between seasons. The estimated value of Pb in the muscles of *C. gariepinus* from all areas in both seasons was 0.7 6 µg/g.

Generally, values of Pb in *C. gariepinus* were below WHO (1990) permissible limits (Table 3) in all areas except the mouth of the Luika River.

Lead (Pb) contamination in *O. esculentus*

The concentration of Pb in *O.*

	Permissible Heavy Metal Limit	
	Metal	
National and International Standards ^{19, 20, 29-33}	PB	HG
Bureau of Indian Standards, 1991	0.1	0.001
Egyptian Organization for Standardization and Quality Control, 1993	0.1	0.1
Provisional Tolerable Weekly Intake (PTWI in ug) by WHO/FAO, 1994	50	0.043
WHO, 1990	1.5	0.14
Food Standards Australia New Zealand, 2002	0.5	—
Food Safety Law and Regulation Singapore, 1990	2	0.5
Malaysia—Food and Agricultural Import Regulations and Standards, 1985	2	0.5

Table 2 — National and International Permissible Limits of Mercury (Hg) and Lead (Pb) µg/g in Fish
* units given in µg/kg

esculentus from the lake and rivers showed a wide variation, between 0.02 to 0.9 µg/g and 0.04 to 1.4 µg/g, respectively. The lowest value of Pb (0.23±0.03 µg/g) in the muscle samples from the rivers was recorded in the rainy season at the middle of the River Songwe (Table 1). The highest (0.98±0.04 µg/g) value of Pb in the muscle samples of *O. esculentus* from the rivers was recorded from the mouth of Songwe River in the dry season. The lowest value (0.17±0.03 µg/g) of Pb in the Lake was recorded from Maleza during rain season. The highest (0.73±0.01 µg/g) levels of Pb were obtained at Kambi Potea during the dry season (Table 1). The concentration of Pb from the Luika and Songwe River did not vary significantly from the values recorded at Maleza and Kambi Potea (P>0.05). The mean value of Pb in the muscles

of *O. esculentus* from all areas, regardless of season, was 0.91 µg/g. There was no seasonal variation in the concentration of Pb (P>0.05). Traces of Pb in *O. esculentus* recorded from all areas were below WHO (1990) permissible limits (Table 3) signifying that individual fish from study areas do not have any health risks related to Pb contamination.

Lead (Pb) contamination in *O. rukwaensis*

O. rukwaensis were obtained from the sites found in the lake. Levels of Pb contamination in *O. rukwaensis* muscles ranged from 0.12 to 0.88 µg/g. The lowest (0.4±0.05 µg/g) and highest mean value (0.77±0.03 µg/g) of Pb in the muscles tissues were recorded from Maleza during the dry and wet seasons, respectively. However, levels of Pb measured at

Maleza did not vary significantly from the one recorded at Kambi Potea (P>0.05). The estimated mean concentration of Pb in the muscles of *O. rukwaensis* collected during dry and rain seasons was 1.125 µg/g. Levels of Pb concentrations in the muscles of *O. rukwaensis* were below WHO (1990) permissible limits (Table 3) indicating that individual fish do not have any health risks related to Pb contamination.

Mercury (Hg) Contamination in *C. gariepinus*

Hg levels varied greatly from one site to another (Table 1). Levels of Hg in the muscles of *C. gariepinus* ranged between 0.03 to 0.33 µg/g. The lowest mean levels of Hg were obtained at the mouth of the Rungwa River (0.01±0.001 µg/g) and at the middle site of the Momba River (0.01±0.006 µg/g). The highest (0.27±0.016 µg/g) mean levels of the same element in rivers were recorded from the mouth of the Luika River. The concentration of Hg obtained from the Luika and Songwe rivers in the southern part was considerably higher than the values recorded from the Momba and Rungwa rivers in the northern and western part of the lake (P<0.05), indicating that *C. gariepinus* from the former areas are more contaminated than those from the latter study areas. Hg contamination at Maleza and Kambi Potea were significantly higher than the values recorded from Momba and Rungwa (P<0.05). On the other hand, the concentration of Hg in the fish from Luika and Songwe rivers were not statistically different to that of Maleza and Kambi Potea (P>0.05). The mean concentration of Hg from all areas of the river in both seasons was 0.2 µg/g. Unfortunately, levels of Hg in all areas in the southern part of the lake were beyond WHO (1990), Bureau of Indian Standards) (1991) India and Egyptian Organization for Standardization

Study Sites	Sediments			
	Lead (PB)		Mercury (HG)	
	Rainy Season	Dry Season	Rainy Season	Dry Season
*Maleza	13.93±1.03	10.55±0.15	0.23±0.002	0.21±0.002
*Kambi Potea	11.4±0.5	9.83±0.76	0.15±0.001	0.14±0.005
Luika River Mouth	14.53±1.06	11.87±2.01	0.32±0.006	0.234±0.033
Luika River Middle	11.8±1.11	10.42±1.12	0.23±0.01	0.22±0.03
Luika River Upper	13.97±	9.05±1.18	0.21±0.004	0.2±0.01
Sogwe River Mouth	13.63±1.26	11.52±1.04	0.25±0.03	0.28±0.012
Songwe River Middle	11.05±1.15	9.91±0.08	0.22±0.002	0.19±0.005
Songwe River Upper	9.83±0.7	8.17±1.01	0.17±0.01	0.03±0.002
Rungwa River Mouth	0.01±0.001	0.02±0.0003	0.02±0.001	0.08±0.004
Rungwa River Middle	ND	ND	ND	ND
Rungwa River Upper	ND	ND	ND	ND
Momba River Mouth	0.01±0.0001	0.002±0.001	ND	ND
Momba River Middle	ND	ND	ND	ND
Momba River Upper	ND	ND	ND	ND

Table 3 — Concentration of Mercury (Hg) and Lead (Pb) in Sediment Collected from Lake Rukwa and Catchment Areas
ND—Not Detected

and Quality Control (EOS) (1993) permissible limits of 1.5 µg/g, 0.001 µg/g and 0.1 µg/g, respectively. These results indicate that individual fish from the study area are not safe for human consumption due to Hg contamination. On the contrary, Hg levels in fish muscles from Momba and Rungwa Rivers in the northern and western part of the lake were below WHO (1990) Permissible limits of 1.5 µg/g (Table 3).

Mercury (Hg) contamination in O. esculentus
Mercury (Hg) concentration

ranged between <0.01 to 0.29 µg/g. The lowest recorded mean value (0.11±0.0001 µg/g) of Hg from rivers was recorded from the middle site of the Songwe River. The highest values (0.23±0.06 µg/g) of Hg were recorded at the mouth of the Luika River. The lowest value (0.11±0.003 µg/g) of Hg from the lake was recorded at Kambi Potea. The highest value of 0.16±0.003 µg/g was measured from Maleza. The concentration of Hg from all areas of the Luika and Songwe rivers were not statistically different from the concentrations measured

from Maleza and Kambi Potea (P>0.05). Mean values of Hg for all areas during the dry and wet season was 0.28 µg/g. The value of Hg from the Maleza, Luika River and Songwe River mouth were beyond the WHO (1990) permissible limits of 0.14 µg/g. Hg values obtained from Kambi Potea and at the middle site of the Songwe River were very close to 0.14 µg/g, which suggest that *O. esculentus* from the study areas are not safe for human consumption.

Mercury (Hg) contamination in O. rukwaensis

The lowest (0.09±0.001 µg/g) mean concentration of Hg was measured from Kambi Potea. The highest value of 0.11±0.07 µg/g was recorded from Maleza. The concentration of Hg at Maleza was not significantly different from the concentration of the same element in the muscle tissue of *O. rukwaensis* from Kambi Potea (P>0.05). The mean concentration of the combined data for Hg in the muscles of *O. rukwaensis* for the samples collected during the dry and wet season was 0.28 µg/g. Values of Hg at Maleza and Kambi Potea were below WHO (1990) permissible limits, indicating that *O. rukwaensis* from the study sites are safe for human consumption.

Lead (Pb) contamination in sediment
Pb concentrations in sediments from the lake and its catchment area showed notable variations (Table 3). The concentration of Pb in river sediment samples ranged between 0.02 to 16.23 µg/g and from 5.12 to 14.8 µg/g in lake sediment samples. The lowest (0.01±0.0001) value of Pb in the river samples were obtained from the mouth of the Momba River. The highest (14.53±1.06 µg/g) mean levels of Pb in river samples were measured at the mouth of Luika River (Table 3). The concentration of Pb in sediment from the Luika

and Songwe rivers was higher than the concentration of the same elements measured from the Momba and Rungwa rivers ($P < 0.05$). Also, the lowest ($9.83 \pm 0.76 \mu\text{g/g}$) and highest ($13.93 \pm 1.03 \mu\text{g/g}$) mean concentration of Pb were recorded from Kambi Potea and Maleza, respectively (Table 3). The mean Pb concentrations in the sediment for both the dry and wet seasons was $15.13 \mu\text{g/g}$. There were no significant differences in the levels of Pb in the sediments from Maleza and Kambi Potea ($P > 0.05$). However, values of Pb at Maleza and Kambi Potea were significantly higher than that of Momba and Rungwa rivers ($P < 0.05$). Small values of Pb in the sediments from the Rungwa and Momba rivers were detected in the river mouth but not in the upper and middle sampling sites (Table 3). There were no differences in the concentration of Pb between the rain and dry season ($P > 0.05$). The concentrations of Pb in the sediments were below Florida's 'No effect level' of $21 \mu\text{g/g}$ and on the threshold of Environment Canada's 'effect level' of $30.2 \mu\text{g/g}$.

Mercury (Hg) contamination in sediment

Mercury concentrations in lake and river sediment samples from the southern part of the lake and its catchment area showed remarkable differences between the sediment from the Rungwa and Momba rivers (Table 3). Hg concentration in the rivers ranged from 0.01 to $1.43 \mu\text{g/g}$ (Table 3). The concentration of Hg in the sediments from the lake ranged between 0.24 to $0.41 \mu\text{g/g}$ at Kambi Potea and Maleza, respectively. The lowest ($0.02 \pm 0.001 \mu\text{g/g}$) mean concentration of Hg in the sediments was recorded from the Rungwa river mouth. The highest ($0.32 \pm 0.006 \mu\text{g/g}$) mean concentrations of Hg in the sediment samples from the rivers were recorded from the mouth of the

Luika River. The lowest ($0.14 \pm 0.005 \mu\text{g/g}$) of the lake sediment samples was recorded from Kambi Potea while the highest ($0.23 \pm 0.002 \mu\text{g/g}$) was measured from Maleza.

The mean concentration of Hg in the dry and wet seasons was $0.39 \mu\text{g/g}$. The study did not reveal a correlation between Hg and Pb in the sediment samples and in fish muscle ($P > 0.05$). There were no differences between Hg levels measured during the dry and rainy seasons ($P < 0.05$). Generally, concentrations of Hg in the sediment were below Florida's 'No effect level' and on the threshold of the 'effect level' of Environment Canada.^{23,24}

Discussion

Mercury and lead accumulation in seafood, water and fish products is a growing global concern that poses severe health risks to the public and ecosystem. In view of the fact that fish have many health benefits as an excellent source of protein, it is imperative to be equally aware of the risks of heavy metals in the environment and the fish we consume. While the health risks of mercury and lead poisoning may perhaps appear like a good reason to abstain from consuming fish, the benefits of eating fish may outweigh many of the dangers. This is because fish is known for its high levels of protein, low in saturated fats, and contains essential nutrients such as omega-3 fatty acids. Furthermore, Docosahexaenoic acid (DHA) is one of the vital fatty acids found in fish oil and is responsible for normal development and functioning of the human brain.²⁵ Therefore, given the ecological as well as economic and health importance of fish to the communities around Lake Rukwa and beyond, the present study explored various guidelines to ascertain and understand the associated health

effects of consuming fish contaminated with mercury and lead, so that well-informed decisions about the fish we consume can be made.

The present study observed Hg and Pb contamination in the muscles of *C. gariepinus*, *O. esculentus* and *O. rukwaensis*. Levels of contamination varied between species as well as sampling locations. The mean concentrations of heavy metals in *C. gariepinus* muscles were higher than in *O. esculentus* and *O. rukwaensis* samples. Higher levels of lead and mercury in the Luika and Songwe rivers indicate that gold mining in the catchment area may contribute to the higher concentration of heavy metals in fish muscles. Although there is no mining activity in the catchments areas of the Momba and Rungwa Rivers, the results indicate that the small quantities of these heavy metals in fish tissues could be associated with water and sediment transport as well as fish movement. Also, this may also be evidence that heavy metals entering the lake through the Luika and Songwe rivers are distributed to the northern part of the lake through hydrological processes. The present study is similar to that of Jezierska and Witesta which found that various heavy metals accumulate in different amounts in fish.²⁶ The concentration of Hg in the muscles of *C. gariepinus* was different from that reported by Ahmed et al. at Assiut Governorate, Egypt.²⁷ The present study did not provide evidence for seasonal differences in the muscle tissues of fish. Conversely, Ahmed et al. reported seasonal variations in the levels of Hg and Pb, with the highest levels being recorded in summer.²⁷ Higher levels of mercury and lead in the muscles of *C. gariepinus* and *O. esculentus* from rivers may be attributed by the fact that fish in the river habitat are at the top of the food chain, thus tending to accumulate metal from water.²⁸

The concentration of lead in the muscles of fish samples were below WHO permissible limits for all fish species, indicating that they are safe for human consumption.¹⁹ On the contrary, levels of Hg in the muscles of *O. esculentus* from the Maleza and Luika rivers and the Songwe River mouth were beyond the WHO permissible limits of 0.14 µg/g.¹⁹ Furthermore, values of mercury from muscles of the same species obtained from Kambi Potea and at the middle site of the Songwe River were very close to the WHO permissible limits 0.14 µg/g, which is an indication that *O. esculentus* from the 2 areas are not safe for human consumption.¹⁹ Because local communities depend greatly on fish from Lake Rukwa as a source of animal protein, the study assessed the safety of fish using both WHO permissible limits for fish and seafood as well as other international standards such as the FAO/WHO Codex.^{19,21,22} The codex utilizes the mean values of Pb in *C. gariepinus*, *O. esculentus* and *O. rukwaensis* muscle tissue, which are 0.76 µg/g, 0.91 µg/g and 1.12 µg/g, respectively, for all areas during the dry and rainy seasons, demonstrating that selected fish from the areas in the present study are not safe for human consumption. In addition, the study adopted national standards wherein the estimated values of Pb were higher than maximum allowable criteria of 2.0 µg/g and 2.0 µg/g wet weight in fish muscles by the Malaysia—Food and Agricultural Import Regulations and Standards (MRF) and Food Safety Law and Regulation Singapore (FRS) (Table 2).^{29,30} That is, fish species collected from Lake Rukwa and its catchment areas are safe for human consumption according to these standards. Conversely, these values were found to be above the tolerable limits of 0.1, 0.1 and 0.5 µg/g set by BIS, EOS and FSA

Australia, respectively (Table 2).³¹⁻³³ These results suggest that using these tolerable limits, fish from the studied areas are not safe for human consumption and perhaps may cause devastating health impacts.

The present results were also compared with that of the USEPA PTWI of 25 µg/kg body weight. The USEPA recommends a consumption estimate of 340 g of fish per week and 70 kg body weight for an adult human.²⁰ Therefore, given the average concentration of 0.76 µg/g, 0.91 µg/g and 1.12 µg/g, the consumption of each fish species will fall out to a weekly intake of 3.69 µg/kg for *C. gariepinus* (0.76 µg/g × 340g/70kg), 4.42 µg/kg of *O. esculentus* (0.91 µg/g × 340g/70kg) and 5.44 µg/kg of *O. rukwaensis* (1.12 µg/g × 340g/70kg) muscle tissues, respectively. The USEPA PTWI of 25 µg/kg was considerably higher than the present weekly intake of 3.69, 4.42 and 5.44 µg/kg for *C. gariepinus*, *O. esculentus* and *O. rukwaensis* muscle tissues. This is an indication that if USEPA PTWI criteria are adopted, fish from Lake Rukwa and its catchment areas are considered safe for human consumption. However, the safety of consumption of the contaminated fish from Lake Rukwa cannot be guaranteed by the present study because communities living around the lake, especially those involved in fishing, depend greatly on fish as a major source of protein. Therefore, it is likely that they may consume quantities of Pb beyond the USEPA PTWI permissible limits. Also, the standards do not consider special groups such as children and pregnant and lactating women. It has also been noted that high concentrations of heavy metals in water can result in fish stunting, especially in early life stages such as hatching, larva development and juvenile growth.¹⁴

The present study determined the levels of lead and mercury in the muscle tissue; however, Ibrahim, Osman and Kloas and Osman discovered considerably higher levels of the metals in the liver than in the muscle tissues in some Nile fishes, *O. niloticus* and *C. gariepinus*.³⁴⁻³⁶ Thus, the present study could have underestimated the total levels of mercury and lead in the fish because it did not consider liver and other active tissues such as fins during analysis. Furthermore, different patterns of heavy metal accumulation and distribution among the muscles tissues and localities in the tissues of *C. gariepinus*, *O. esculentus* and *O. rukwaensis* suggest that fish species have differential abilities to absorb heavy metals from feeding diets, sediment and surrounding environment.³⁷ Differences in the concentrations of heavy metals in the tissues of freshwater fishes among different studies may perhaps be caused by variations of metal concentrations in water and sediment from which fish were sampled, ecological needs, metabolism and feeding patterns.³⁸⁻⁴⁰ For example, *C. gariepinus* was observed to have a higher risk of contamination by Pb and Hg because of its benthopelagic (bottom dwelling) omnivorous feeding behavior. Its diet normally consists of insects, crabs, plankton, snails, and fish, but it also has been observed to consume young birds, rotten flesh, plants and fruit.⁴¹ Also, biotransformation mechanisms developed by the species and its adaptability to chemicals may cause differences in the levels of heavy metal in the present study.⁴² In addition, physicochemical characteristics such as water temperature, pH, conductivity, rainfall, hardness, salinity and biotic community interactions influence levels of pollution in fish.⁴³ It is likely that differential accumulation

of heavy metals in the present study could be caused by different microhabitat utilization, fish species and probably species home range and exposure time.

In this study, sediment samples were considered important indicators for Hg and Pb pollution because previously it has been reported that sediment acts as a permanent or temporary trap for material spread into the environment.⁴⁴ Sediment has frequently been analyzed to identify sources of trace metal in the aquatic environment because it exhibits high accumulation rates.³⁴ Higher concentrations of Hg and Pb in the Luika and Songwe rivers than the Momba and Rungwa rivers provide evidence for considerable contribution of gold mining operations in the catchment area. This implies that fish surviving in these polluted areas accumulate higher levels of heavy metals than those surviving at less polluted areas, as reported in other studies.^{34,45,46} Traces of heavy metals were not uncovered in the upper and middle sections of the Rungwa and Momba rivers, possibly due to the lack of anthropogenic activities with Hg and Pb. However, the presence of heavy metals in the sediment from the mouths of the same rivers suggests a mechanism of sediment transport from southern to northern and western parts of the lake. Also, the study revealed that mercury in the sediment samples was not statistically higher than in the fish samples despite the fact that Kock and Hofer reported that even low concentrations of heavy metal in the water may result in high concentrations in fish flesh.⁴⁷ This is because accumulation of heavy metals in fish muscles may be caused by its strong binding with cystine residues of metallothionein.⁴⁸ According to the present results,

levels of Pb and Hg were below the state of Florida's 'No effect level' and at the threshold 'effect level' of Environment Canada. The present results should be considered keeping in mind that mercury and lead are very toxic even at low levels.^{48,49}

Conclusion

The present results indicated variable levels of Hg and Pb in the muscles of fish and sediment samples. Pb in fish muscles were below WHO and USEPA PTWI standards. However, it is important to keep in mind that for many people living around the lake, fish plays an important health role as a major source of animal protein. Thus, people living around the study areas are likely to consume more fish than considered by the USEPA PTWI and other international and national standards. The levels of Hg in the muscles of *C. gariepinus* and *O. esculentus* collected from the southern part of the lake were higher than recommended by the WHO, demonstrating that fish from the study areas are not safe for human consumption. The study recommends further research on the levels of Hg and Pb in humans, especially children and pregnant women. Further research on the effects of Hg and Pb on the growth of fish is recommended.

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References

1. Bwathondi PO. An appraisal on fish and fishery of Lake Rukwa. Dar es Salaam: Ministry of Natural Resources and Tourism of United Republic of Tanzania; 1990.
2. Malm J, William R, Rull F. Effect of mercury on mortality and growth. *Marine Pollut Bull.* 1995;2(12):182-7.
3. Telmer KH, Veiga MM. World Emissions of mercury from artisanal and small scale gold mining. In: Mason R, Pirrone N, editors. Mercury fate and transport in the global atmosphere: measurements, models and policy implications. Nairobi: United National Environmental Programme; 2008 Jul 14.
4. Tanushree B, Chakraborty S, Bhumika F, Piyal B. Heavy metal concentrations in street and leaf deposited dust in Anand city, India. *Res J Chem Sci* [Internet]. 2011 Aug [cited 2015 Apr 14];1(5):61-6. Available from: http://www.isca.in/rjcs/Archives/vol1/15/ISCA_RJCS_10_2011_110.pdf
5. Iorfa AC, Ntonzi NT, Ukwang EE, Abara IK, Neji P. A study of the distribution pattern of heavy metals in surface soils around Arufu Pb-Zn mine, Northeastern Nigeria, using factor analysis. *Res J Chem Sci* [Internet]. 2011 May [cited 2015 Apr 14];1(2):70-80. Available from: <http://www.isca.in/rjcs/Archives/vol1/12/10.pdf>
6. Reddy GB, Madhusudana RB., Venkata RN, Sashidhar C. Effect of heavy metal and magnesium sulfate on properties of blended cement mortar. *Res J Chem Sci* [Internet]. 2011 Oct [cited 2015 Apr 20];1(7):27-32. Available from: <http://www.isca.in/rjcs/Archives/vol1/17/11704ISCA-RJCS-2011-127.pdf>
7. Guedenon P, Edorh AP, Hounkpatin AS, Alimba CG, Ogunkanmi A, Nwokejiegbegbe EG, Boko M. Acute toxicity of mercury (HgCl₂) to African Catfish, *Clarias gariepinus*. *Res J Chem Sci* [Internet]. 2012 Mar [cited 2015 Apr 20];2(3):41-5. Available from: <http://www.isca.in/rjcs/Archives/vol2/i3/7.ISCA-RJCS-2012-006%20Done.pdf>
8. Ubalua AO, Chijioke UC, Ezeronye OU. Determination and assessment of heavy metal content in fish and shellfish in Aba River Abia State Nigeria. *KIMITL Sci Tech J* [Internet]. 2007 Jan-Jun [cited 2015 Apr 20];7(1):16-23. Available from: <http://www.kmitl.ac.th/ejkmittl/vol7no1/3-p16-23.pdf>
9. Matsuo J. Fish as a bioindicator by freshwater contamination by metal. *Pakistan J Agric Sci.* 2003;35:11-5.
10. Olaifa FE, Olaifa AK, Onwude TE. Lethal and sublethal effects of copper to the African Catfish

(*Clarias gariepinus*) juveniles. *Afr J Biomed Res* [Internet]. 2004 [cited 2015 Apr 20];7(2): 65-70. Available from: <http://www.ajol.info/index.php/ajbr/article/view/54071/42611>

11. Micryakov VR, Lapirova TB. Influence of salts of some heavy metals on the differential blood count in juvenile *Acipenser baeri*. *J Ichthyology*. 1997;37(6):458-62.

12. Yaduma JB, Humphrey MM. Accumulation of some heavy metals in *Clarias anguillaris* and *Heterotis niloticus* from Lake Geriyo Yola Nigeria. *Nat Sci* [Internet]. 2009 [cited 2015 Apr 20];7(12):40-3. Available from: http://www.sciencepub.net/nature/ns0712/07_2029_bennard_ns0712_40_43.pdf

13. Guimaraes JR, Lacerda LD, Teixeira VL. Revista Brasileira de Biologia. 1982. 42:553-7. Portuguese.

14. Heath AG. Water pollution and fish physiology. 1st ed. Florida, USA: CRC press; 1987. 245 p.

15. Mackay D, Clarck KE. Predicting the environmental partitioning of organic contaminants and their transfer to biota. In: Jones KC, editor. Organic contaminants in the environment: Environment management series. New York: Elsevier Science Pub; 1991. Chapter 5.

16. Seegers L. The fishes of the Lake Rukwa drainage. Tervuren Belgium: Royal Museum for Central Africa; 1996. 287 p. (Annales. Sciences zoologiques).

17. Hughes RH, Hughes JS. A directory of African wetland. Gland, Switzerland: International Union for Conservation of Nature; 1992. 820 p.

18. Sreedevi PA, Suresh B, Siraramkrishna B, Prebhavarhi B, Radhakrishnaiah K. Bioaccumulation of nickel in organs of the freshwater fish, *Cyprino carpio* and the freshwater mussel, *Lamellidens marginalis* under lethal and sublethal nickel stress. *Chemosphere*. 1992 Jan;24(1):29-36.

19. Environmental health criteria 101: Methylmercury [Internet]. Geneva, Switzerland: World Health Organization; 1990 [cited 2015 Apr 21]. Available from: <http://www.inchem.org/documents/ehc/ehc/ehc101.htm>

20. Risk assessment: Technical background information, RBG Table. Washington D.C.: United States Environmental Protection Agency; 1994.

21. Report on the 16th session of the codex committee on food additives and contaminants; 2004 Mar 22-26; Rotterdam, The Netherlands. New York: Food and Agriculture Organization.

22. Report of the 38th session of the codex committee on food additives and contaminants:

Provisional agenda; 2006 Apr 22-28; The Hague, The Netherlands. New York: Food and Agriculture Organization; 2016 May.

23. Interim sediment quality assessment values. Ottawa, Canada: Ecosystem Conservation Directorate—Environment Canada; 1994. Manuscript Report No. ECD.

24. MacDonald DD. Development of an approach to the assessment of sediment quality in Florida coastal waters: Development of the sediment quality assessment guidelines. Tallahassee, Florida: Florida Department of Environmental Protection; 1993. 2 Vol.

25. Sakamoto M, Kubota M, Liu XJ, Murata K, Nakai K, Satoh H. Maternal and fetal mercury and n-3 polyunsaturated fatty acids as a risk and benefit of fish consumption to fetus. *Environ Sci Tech* [Internet]. 2004 Jul 15 [cited 2015 Apr 21];38(14):3860-3.

26. Jezierska B, Witeska M. The metal uptake and accumulation in fish living in polluted waters. In: Twardowska I, Allen HE, Haggblom MM, Stefaniak S, editors. *Soil and Water Pollution Monitoring, Protection and Remediation*. Netherlands: Springer; 2006. p. 107-14.

27. Ibrahim AT, Omar HM. Seasonal variation of heavy metals accumulation in muscles of the African Catfish *Clarias gariepinus* and in River Nile water and sediments at Assiut Governorate, Egypt. *J Bio Earth Sci* [Internet]. 2013 Oct 11 [cited 2015 Apr 22];3(2):B236-48. Available from: <http://www.journals.tmkarpinski.com/index.php/jbes/article/view/72/72>

28. Mansour SA, Sidky MM. Ecotoxicological Studies. Heavy metals contaminating water and fish from Fayoum Governorate, Egypt. *Food Chem* [Internet]. 2002 Jul [cited 2015 Apr 22];78(1):15-22. Available from: <http://www.sciencedirect.com/science/article/pii/S0308814601001972> Subscription required to view.

29. MDC legal advisers, compiler. Food act 1983; and, food regulations 1985. 4th ed. Malaysia: MDC Sdn. Bhd.; 1994. 279 p.

30. FRS. Singapore's food regulation: Coconut oil. In: The sale of food act. 1990 ed. Singapore: National printers limited; 1990. Chapter 283.

31. Drinking water specification. New Delhi, India: Bureau of Indian Standards; 1991

32. Maximum level for heavy metal contamination in food. Cairo, Egypt: Egyptian Organization for Standardization and Quality Control; 1993.

33. Food Standards as Amended. Australia New

Zealand food standard code [Internet]. Canberra, Australia: Australia New Zealand Food Authority; 2002 [cited 2015 Apr 22]. Chapter 1: part 1.4 contaminants and residues: standard 1.4.1 - standard 1.4.2. Available from: <http://www.foodstandards.gov.au/code/Pages/default.aspx>

34. Ibrahim AT. Distribution patterns of some heavy metals and pollution induced changes in some organs of three Nile fish species from Assiut, Egypt. Assiut, Egypt: Assiut University; 2007.

35. Osman AG, Kloas W. Water quality and heavy metal monitoring in water, sediments, and tissues of the African Catfish *Clarias gariepinus* (Burchell, 1822) from the River Nile, Egypt. *J Environ Prot* [Internet]. 2010 Dec [cited 2015 Apr 22];1(4):389-400. Available from: <http://www.scrip.org/journal/PaperInformation.aspx?paperID=3381#.VTfDf7-2x>

36. Osman AG. Biomarkers in Nile Tilapia *Oreochromis niloticus niloticus* (Linnaeus, 1758) to assess the impacts of River Nile pollution: Bioaccumulation, biochemical and tissues biomarkers. *J Environ Prot* [Internet]. 2012 Aug [cited 2015 Apr 22];3(8A):966-77. Available from: <http://www.scrip.org/journal/PaperInformation.aspx?PaperID=21781#.VTfQTf7-2w>

37. McCarthy JF, Shugart IR. Biomarkers of environmental contamination. New York: Lewis Publishers; 1996. 425 p.

38. Bahnasawy M, Khidr AA, Dheina N. Assessment of heavy metal concentrations in water, plankton, and fish of Lake Manzala, Egypt. *Turk J Zool* [Internet]. 2011 [cited 2015 Apr 22]; 35(2):271-80. Available from: <http://journals.tubitak.gov.tr/zoology/issues/zoo-11-35-2/zoo-35-2-13-0810-6.pdf>

39. Nwabueze AA, Oghenevwaire E. Heavy metal concentrations in the west African clam, *Egeria radiata* (Lammark, 1804) from McIver market, Warri, Nigeria. *Int J Sci Nature* [Internet]. 2012 [cited 2015 Apr 22];3(2):309-15. Available from: [http://www.scienceandnature.org/IJNS_Vol3\(2\)2012/IJNS-VOL3\(2\)12-15.pdf](http://www.scienceandnature.org/IJNS_Vol3(2)2012/IJNS-VOL3(2)12-15.pdf)

40. Papagiannis I, Kagalou I, Leonardos J, Petridis D, Kalfakakou V. Copper and zinc in four freshwater fish species from Lake Pamvotis (Greece). *Environ Int* [Internet]. 2004 May [cited 2015 Apr 22];30(3):357-62. Available from: <http://www.sciencedirect.com/science/article/pii/S0160412003001879> Subscription required to view.

41. Teugels G. A systemic revision of the African species of the genus *Clarias* (Pisces: Clariidae). Flanders, Belgium: Annales Musee Royal de l'Afrique

Centrale; 1986. 247 p.

42. Nziku A, Namkinga L. Heavy metal pollution in the receiving environment of the University of Dar Es Salaam waste stabilization ponds. *J Biol Life Sci* [Internet]. 2013 [cited 2015 Apr 22];4(1):205-18. Available from: <http://www.macrothink.org/journal/index.php/jbils/article/view/3084>

43. Arvinda K. Ecology of polluted waters. New Delhi: A.P.H Publishing Corporation; 2002. 290 p.

44. DeGregori I, Pinochet H, Arancibia M, Vidal A. Grain size effect on trace metals distribution in sediments from two coastal areas of Chile. *Bull Environ Contam Toxicol* [Internet]. 1996 Jul [cited 2015 Apr 22];57(1):63-70. Available from: <http://link.springer.com/article/10.1007/s001289900170> Subscription required to view.

45. Sayed MM. Toxicological studies on some metallic pollutants in River Nile at Assiut Governorate [Ph.D. Thesis]. [Assiut, Egypt]: Assiut University; 1995.

46. Ohaida AM. The effect of lead and its interaction with supplementation of selenium and vitamin E on the growth performance, biochemical and physiological characteristics, histopathology and cytopathology of *Oreochromis niloticus* [Ph.D Thesis]. [Assiut, Egypt]: Assiut University; 2005. 218 p.

47. Kock G, Hofer R. Origin of cadmium and lead in clear soft water lakes of high-altitude and high latitude, and their bioavailability and toxicity to fish. *J Exs.* 1998;86:225-57.

48. Tayel S, Yacoub AM, Mahmoud S. Histopathological and haematological responses to freshwater pollution in the Nile Catfish *Clarias gariepinus*. *J Egypt Acad Soc Environ Dev.* 2008;9:43-60.

49. El-Naggar SM, Tayel S. Bioaccumulation of some heavy metals and histopathological alterations in liver of *Oreochromis niloticus* in relation to water quality at different localities along the River Nile, Egypt. *World J Fish Marine Sci.* 2009;1(2):105-14